METHOD AND APPARATUS FOR DIAGNOSING A CYCLIC SYSTEM

FIELD OF INVENTION:

5   The present invention relates to a method and apparatus for diagnosing a cyclic system and more specifically for diagnosing the operational status of a fluid power system.

BACKGROUND OF THE INVENTION:

          In the manufacturing environment, various systems are employed in order to
10   operate machinery and transport goods. In order to achieve consistent output and continuity in the various systems, frequent maintenance and trouble shooting is often required. One manor of maintaining machinery is to wait until a failure has occurred in a particular component and then replace that component on an as-needed basis. Such maintenance, however, often requires untimely interruptions of the production
15   process leading to costly down time.

          Accordingly, there has been a growing trend in machinery maintenance to employ preventative maintenance procedures so that a machine is not brought down by an untimely failure. Instead, maintenance may be performed during planned down times with various components being serviced in an efficient process. However, since
20   preventative maintenance often requires replacement of components before they actually fail, it must be determined which part is in need of replacement or repair and when. One way to determine the replacement scheduling of components would be to assign a particular cycle life to a component and simply replace that component after it has achieved its predetermined cycle life. However, how long a component will
25   remain operationally effective depends on a variety of factors. For example, in a pneumatic system, the level of contamination in the pressurized air, the lubrication used, the operating pressure, ambient environment, and cycle speeds are just a few of the factors, which will influence cycle life. Accordingly, this method of preventative maintenance can lead to the replacement of parts, which are in fine working order
30   creating a wasteful and relatively expensive procedure.

There have been attempts to use more sophisticated means of predicting when a component will fail in a particular system. One such method of predetermining component failure is set forth in EP 0740805 A1. The system set forth in the patent publication includes the use of a transducer, a learning mode, data collection at

5   predetermined multiple points within a cycle, and memory operable during a learning mode. During a cycle digital sample signals may be taken at 100 to 1000 points of the cycle. It also includes a means for providing permissible ranges of values at the predetermined points in comparison between actual data and data of a learning mode and means to provide an output signal if the actual data exceeds the permissible data

10   on predetermined points. This method, however, requires significant memory space in order to store the many data points in the cycle. In addition, high computational speed is needed for comparing the data at each point in the cycle with the predetermined range of data values. Complex mathematical statistical evaluation is also required.

15   U.S. Patent No. 5,329,465 is directed to an on-line valve diagnostic monitoring system. The system senses operational characteristics of a valve and provides a diagnosis of the aberrations in the system characteristics. Multiple sensors are used which then signal to a data acquisition system which can be transmitted to remote locations. In a pneumatically controlled valve, a pressure sensor or flow meter

20   may be used to detect the air pressure required to actuate the valve. A stem strength sensing means for directly sensing tension and compression of the valve stem is also required for sensing the position of the valve and travel the valve stem. Accordingly, various sensors are used and a significant amount of data is collected.

In addition, the use of individual system characteristics has heretofore proven

25   to be unacceptable for providing a reliable picture of system performance for determining periodic maintenance schedules. For example, in a pneumatic system, pressure measurements in the supply and exhaust lines of a valve or a cylinder only deliver information about the cylinder functions which are in most cases independent of valve functions. While pressure measurements may provide diagnostic information

30   with regard to cylinder function, it does not provide sufficient diagnostic data for valve functions.

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Flow measurements in a supply line in a pneumatic circuit delivers information about the functions of the entire pneumatic circuit. The information about cylinder functions would be limited for a time depending function, thus not permitting to differentiate between cylinder failures and other possible failures, e.g.,

5 malfunction of valve, clogged silencer, etc. The flow measurement improves the diagnosis for pneumatic circuit, but still does not provide sufficient diagnosis data for all functions.

Another measurement which can be taken is cycle time for a complete cycle of the circuit. The cycle time measurement delivers information about the functions of

10 the entire pneumatic circuit, including information about cylinder and valve functions. However, this cycle time does not provide sufficient diagnostic data to determine whether a particular component is nearing failure.

Accordingly, it would be desirable to provide a method and apparatus for evaluating a cyclical system in order to determine when preventative maintenance

15 should be performed. It is further desirable to provide such a method and apparatus which requires minimal collection of data and can be easily and inexpensively employed.

SUMMARY OF THE INVENTION:

It is an advantage of the present invention to provide a method and apparatus

20 for diagnosing a cyclic system.

It is another advantage of the present invention to provide a method for diagnosing the operational status of a fluid power system using one system characteristic.

In the efficient attainment of these and other advantages the present invention

25 provides a method and apparatus for determining the service life of a cyclic system. The method includes the steps of determining at least one characteristic of the system to determine a characteristic value and determining a cycle time of the system. The at least one characteristic value is applied to an algorithm in which the characteristic value is integrated to determine a diagnostic value, and comparing the diagnostic

30 value to a predetermined value to determine the operational status of the system.

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The apparatus includes a sensor for determining a system characteristic and a calculating unit operatively connected to the sensor. The calculating unit includes circuitry for performing a mathematical integration on the system characteristic to determine a diagnostic value and compares the diagnostic valve to a predetermined value to determine the performance status of the system. A notification device is operatively connected to the calculating unit for indicating the operational status of the system.

In a preferred form of the invention, the characteristic value is flow rate Q and the algorithm to determine the status of the system is

$$K = \int_0^T Q dt$$ wherein Q is the flow rate, T is the cycle time and K is the diagnostic value.

The present invention further provides a cyclic fluid power system having an operational status monitor including a valve in fluid communication with a fluid source. An actuator is operatively connected to the valve. A sensor is provided for determining a system characteristic. A calculating unit is operatively connected to the sensor. The calculating unit includes circuitry for performing a mathematical algorithm on the system characteristic to determine a diagnostic value and compares the diagnostic value to a predetermined value to determine the performance status of the system. A notification device is operatively connected to the calculating unit for indicating the operational status of the system.

For a better understanding of the present invention, reference is made to the following detailed description to be read in conjunction with the accompanying drawings and the scope will be defined in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 is a schematic diagram of a cyclic system including the apparatus of the present invention.

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Figure 2 is a graphical representation of system parameters valve actuation voltage u, pressure p, flow Q, and piston movement s verses time.

Figure 3 is a graphical representation of flow rate Q verses time T showing a normal condition and a leak condition.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS:

The present invention provides a method and apparatus for providing diagnostic information for determining the operational or performance status of a system for preventative maintenance purposes. The present invention permits the prediction of failures in a fluid power circuit including determination of possibly failing components and failure causes. A prediction of the life cycle of the system or its components under the conditions of a particular application may also be obtained. The present invention uses a minimum number of sensors in the system in order to provide the necessary information.

Referring to Figure 1, a fluid power system, such as pneumatic system 10, generally includes a valve 12, which is operatively connected to an actuator 14. Actuator 14 may include a drive component 14a such as a piston which is attached to a piston rod 14b. The valve 12 receives a signal from a controller 16, which causes the valve 12 to shift at the predetermined time when movement of the actuator 14 is desired. A system may include a plurality of valves and actuators with the controller coordinating the actuation of the various valves in order to achieve the desired actuator response. In a cyclic system, the system is designed to operate through a particular repeatable cycle. Accordingly, the actuation of the valve and corresponding actuator movement is repeated many times. The present invention utilizes variations in a system characteristic over time in order to determine the operational fitness of the system and its components.

The present invention preferably utilizes one characteristic of the system to predict failures. In the preferred embodiment, the system characteristic is the flow rate Q. Integrating the flow rate Q over the cycle time T provides a diagnostic value K, also referred to as the flow integral, which can be used to predict preventative

maintenance requirements. Specifically, the diagnostic value K is calculated using the following algorithm:

$$K = \int_0^T Q dt$$

wherein Q = flow rate and T = cycle time.

5   The characteristic value of the system, i.e. flow rate, can be measured by a transducer or sensor of a type which is known in the art. By integrating the flow rate Q over a certain time period, the volume of fluid consumed for that period is determined. A change in the amount of fluid consumed is indicative of changes in the system's operational status. For example, a system that is leaking air will consume more air 10   than when it was not leaking resulting in an increase in the K value. This change in the diagnostic value is used to indicate that maintenance is required.

    The integration may be performed in calculating unit 20 shown schematically in Figure 1. Calculating unit 20 may include a processor 20a that may be in the form of a microprocessor or in the form of discrete components such as op amps and 15   resisters. If a digital microprocessor is employed, an analog to digital converter 20c may be used to convert an analog signal generated by the sensor to a digital signal, which can be processed by the microprocessor. Calculation unit 20 may also include a memory storage device 20b to temporarily store information used in the calculation process.

20   The integration of Q is preferably done over cycle time T. Cycle time T may be the time for one complete cycle of a cyclic system. For example, as shown in Figure 2, in a cyclic pneumatic system including a valve and piston driven cylinder, the full cycle time, T, includes the time from valve actuation t_1 until the cylinder piston has returned to its initial position t_5. Cycle time T may be measured and 25   calculated by a programmable logic controller, PLC, which may also be used to control the entire fluid power system. Cycle time T would be the time it takes to complete one cycle. Alternatively, the cycle time T may be calculated using limit switches on a fluid power actuator, such as a linear drive, with the limit switches indicating the two end positions of the cylinder and wherein movement of the piston

from one end to the other and back again constitutes one cycle. In a preferred embodiment, cycle time T may equal the entire time for one complete cycle as shown in Figure 2. One complete cycle being the time period defined by an actuation of the valve t_1 and a return of the piston to an initial position t_5. By integrating over the entire cycle time, any deviation from normal operating parameters may be diagnosed regardless of where the problem occurs in the cycle. Such deviations may include leakage, excess friction, etc.

It is also within the contemplation of the present invention that the period of integration may be chosen to include only part of a full cycle. For example, the integration may be done over the time of piston movement, s, which is period t_2 to t_3 shown in Figure 2. In this case the algorithm would include an integration of Q over time t_2 to t_3. $K = \int_{t2}^{t3} Qdt$ Alternatively, T may equal the time of valve actuation, u,

shown in Figure 2 as time period t_1 to t_4, $K = \int_{t1}^{t4} Qdt$. By limiting the time period to a certain period, a particular component of the system, such as the cylinder, can be more specifically monitored. For example, integrating flow rate Q over the time period t_2 to t_3, provides the diagnostic value K, which in this case is the volume of fluid for the period of piston forward movement. If this value deviates beyond an acceptable parameter, them a problem with the cylinder, such as leakage, may be diagnosed. It is further within the contemplation of the present invention that monitoring of both the entire cycle and portions of the cycle can be performed in order to provide information about the status of the system.

In an alternative embodiment of the present invention, the cycle time use for integrating the flow can be derived from the flow Q itself. The flow rate Q generated by flow sensor 18 can be mathematically differentiated as follows:

$L = dQ/dt$

L, therefore, is the rate of change of the flow over time. In a system having an actuator such as a cylinder, this value can be used to determine the beginning and the end of cylinder movement. It is desirable to integrate the flow Q over this period in the cycle. The ability to determine when cylinder movement begins or ends is useful

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in determining the period over which to integrate the flow in order to determine the diagnostic value K. The behavior of a pneumatic system is graphically represented in Figure 2. This graph depicts the response over time of the valve actuation, or signal, voltage u, pressure p, flow Q and cylinder piston position s.

5   At t_1, the valve actuation voltage, u, is switched on and the valve opens. A minor flow condition occurs as the tubing running to the cylinder is filled with air. The pressure p builds up in the system until the pneumatic force is larger than the frictional and external forces on the piston. At t_2, the cylinder piston starts to move (s > 0). The pressure, p, changes only a small amount depending on the air supply and

10   its ability to supply an adequate amount of air. The flow, Q, sharply rises as air fills the cylinder. The cylinder reaches its end position at t_3 and the flow again sharply changes, this time decreasing significantly between t_3 and t_4. For the time period t_3 to t_4, the cylinder remains at its end position (s = fully extended) and the full pressure, p, is applied to the cylinder piston. The flow Q decreases to zero depending on

15   compressibility, leakage and other factors. After t_4, the solenoid voltage u is zero. The pressure p decreases to zero, and the piston may return to its original position (s = 0) with the flow being negligible. At t_5, the piston has returned to its initial position.

As demonstrated by the graph of Figure 2, the flow Q has well defined changes in its slope, or rate of change, at t_2 and t_3 which is the period of piston

20   movement. When a fluid power cylinder piston begins to move, the flow rate changes rapidly as the fluid fills the ever-increasing volume created by the moving piston. This sharp change in flow rate, which occurs upon piston movement, can be detected by differentiating the flow that results in a rate of change value. Likewise, when the cylinder piston comes to an end position, the flow decreases sharply as the cylinder

25   volume becomes fixed. The significant rate of change of the flow at t_3 can be easily calculated by differentiating the flow. The calculation device can be configured, such as through software, to look for a predetermined rate of change of the flow Q, dQ/dt, at or above a certain value. For example, a positive predetermined increase in the flow rate would indicate the time t_2 for integration purposes and a predetermined

30   decrease in the flow rate would indicate the time t_3 for integration purposes in the algorithm $K = \int_{t2}^{t3} Q dt$. In this case, T equals t_3-t_2. Accordingly, the start and stop time

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of a fluid power cylinder can be determined by differentiating the flow rate Q. While the piston movement could be determined using positioned sensors, the use of the value L eliminates the need, and associated expense and complexity, for extra components. In the present invention, the flow is already sensed to determine the diagnostic K value; therefore, no additional sensors are required. The calculation unit that is configured to integrate the flow can also be configured to process the differential of the flow L.

It has been found that the diagnostic value K, also referred to as the flow integral, varies with the operational condition of the system. Therefore, it can be used for diagnosis and enables an easy statistical analysis and/or pattern recognition with a failure diagnosis of the pneumatic system or circuit. The integration of system flow over the cycle time provides the volume of fluid employed in a given cycle. In a fluid power system, as the components wear and reach the end of their cycle life, seals begin to degrade. Such degradation allows air to flow past the seals causing a leaking condition. Figure 3 illustrates graphically a leak condition in which case the volume of fluid increases over the normal volume of a non-leaking system. This increase in volume is reflected in the diagnostic value K that is an integral of the flow rate Q. In a pneumatic cylinder if the seals are worn to permit leakage, the flow to move that particular cylinder is increased. In addition, if bearings on a pneumatic cylinder begin to wear causing increased loading on the system, more pressure will be required to move the cylinder. In order to have this increased pressure, a greater volume of air is required. Therefore, the flow would also show an increase. Accordingly, a change in the volume of fluid per cycle indicates a system whose components are beginning to fail. It is the integration of the flow over cycle time which averages out peeks and valleys caused by temporary events thereby eliminating unwanted influences on measuring. Accordingly, changes in the diagnostic value K demonstrate a change in the operational condition of the system and are used to alert operators of the need to perform maintenance.

The calculated K values may be subjected to statistical analysis in order to develop a trend in changing K values. For example, the K values generated may be sampled over a predetermined number of cycles and averaged to determine a mean value, which is then compared to an acceptable range of deviation. In this example,

the K value for every 100 cycles could be captured and averaged over 1000 cycles. The average K value would then be evaluated to determine system condition. It is within the contemplation of the present invention that any of a number of statistical methods well known in the art could be employed to determine an average or mean K

5   value, K_{ave}.

In order to determine the acceptable limit of K values for a particular system, a system having new components may be initially run to determine a particular diagnostic K value for that system. This could be done for each individual system. Alternatively, if several systems are being produced having the same design, then a

10   diagnostic value could be determined for one such system and applied to the other similar systems. Depending on the system, an acceptable change in K value would be established. This could be set up as a range or a percentage change in the value. If the diagnostic value K changes a certain percentage or falls outside a particular range, a signal could be sent to an operator indicating that the circuit is in need of

15   maintenance.

The present invention may be employed in a wide variety of cyclic systems. In the preferred embodiment, as shown in the schematic of Figure 1, the present invention is employed in a fluid power system. The fluid power system 10 may include a variety of valves 12 operably connected to actuators 14 by fluid supply lines

20   15. One such valve and actuator is schematically represented in Figure 1. The system 10 may be driven by a control device 16 such as a PLC or other control device as is well known in the art. The control device 16 may be operatively connected to the various valves and actuators that make up the system and generates a control signal 17, which actuates valve 12. The location of flow sensor 18 can be chosen based

25   upon the particular component in the system that is to be monitored. In a pneumatic system including a valve and cylinder, if the sensor were positioned to sense the flow in the fluid supply line to the valve, then the condition of the valve and cylinder would be reflected in the K value. Alternatively, if the sensor were disposed in the system to sense the flow between the valve and cylinder, then the condition of the

30   cylinder would be reflected in the K value. The present invention contemplates that one or more flow sensors could be located in various locations throughout the system to assist in determining the condition of the system and its components.

In operation, the apparatus of the present invention may include flow sensor 18 for monitoring the flow in the system and generating a flow signal 19. Flow sensor 18 may be of a type commercially available and well known in the art, such as an in-line paddle wheel device, which emits a voltage proportional to the sensed flow rate. Flow sensor 18 may be located in the air supply line 15 to valve 12. The flow signal 19 is fed to calculating unit 20. In the preferred embodiment, calculating unit 20 includes a digital microprocessor 20a, a memory storage device 20b, and an analog to digital (A to D) converter 20c. The flow signal 19 may be analog in nature and converted to digital form by A to D converter 20c. Calculating unit may also be operatively connected to controller 16. Controller 16 may provide calculating unit 20 with a cycle time signal 22. Calculation unit 20 alternatively could include an integration circuit consisting of op-amps and resisters as is well known in the art.

Based on information produced by flow signal 19 and cycle time signal 22, the calculation unit 20 integrates the flow rate value Q over cycle time 0 to T to generate the K value. The calculation of the K value may be performed at a predetermined number of cycles and averaged over another predetermined number of cycles. An average K value, K_{ave}, may then calculated by the calculating unit 20. The K_{ave} value is then compared to stored information, which may include an acceptable range of values, to determine if the calculated K_{ave} value is within a particular acceptable range. The result of the comparison may generate system diagnostic information which may displayed on notification device 24 which is operatively connected to the calculation unit. If the calculated K_{ave} is within limits, then a normal operational status may be generated and displayed. The K_{ave} value may also be displayed. If the calculated K_{ave} value falls outside of the acceptable range, an alert may be generated on notification device 24 to alert a user that the system is in need of maintenance. The notification and displays may be in the form of a signal light or audible signal or a message on a visual display. This notification may be displayed on the machine and/or transmitted to a central location such as a plant operator's computer terminal.

In an alternative embodiment, calculation unit 20 may also differentiate the flow value Q to determine the beginning and end of a cycle as set forth above with respect to Figure 2. In this embodiment, the need to have the cycle time signal 22 inputted into calculation unit 20 would be unnecessary.

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Since only one characteristic of the system needs to be tracked, only a limited amount of data need be collected and stored in order to predict the remaining cycle life of the system.

In an alternative embodiment, a change in diagnostic value and a change in cycle times are calculated to provide information regarding the service life of a system. The diagnostic value is evaluated over a plurality of system cycles in order to determine a change in the diagnostic value. The time for completing the cycle time is also evaluated over the plurality of system cycles to determine a change in the cycle time. At predetermined times, the change in the diagnostic value may be compared to the change in the cycle time to determine the performance status of the system. In this embodiment, the diagnostic value K is the integral of the flow Q as described above. It has been found that as this value increases and the cycle time remains the same, leakage problems are occurring in the system. It has also been found that as the cycle diagnostic value K increases and the cycle time increases, there is likely an increase in mechanical load or friction in the cylinder.

In order to implement this process, the calculation unit 20 calculates and stores in memory device 20b K values and cycle times T, T being the time it takes to complete a cycle. At a predetermined number of cycles, the change in cycle times ΔT is calculated, as is the change in diagnostic value ΔK. The ΔT and ΔK are then compared with the results of this comparison and may be outputted to a display or other signal device in order to alert a user of the particular problem, *i.e.*, leakage or increased mechanical load. For example, the diagnostic value K_1 is calculated at a first time period T_1. This diagnostic value at T_1 is compared to the diagnostic value K_2 calculated at a second time period T_2 to determine the diagnostic value delta ΔK, which is $K_2 - K_1$. The cycle time at a first time period T_1 is compared to the cycle time at a second time period T_2 to obtain a cycle time delta ΔT, which is $T_2 - T_1$. The diagnostic value delta ΔK is then compared to the cycle time delta ΔT to obtain an operational status of the system. This method relies only on a flow sensor and a time signal generated by a controller, so there is no need for additional sensors or components.

While there have been described what is presently believed to be the preferred embodiments to the invention, those skilled in the art will realize that various changes

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and modifications may be made to the invention without departing from the scope of the invention, and it is intended to claim all such changes and modifications as fall within the true scope of the invention.